



Design principles for nuclease-deficient CRISPR-based transcriptional regulators

Jensen, Michael K.

Published in:
FEMS Yeast Research

Link to article, DOI:
[10.1093/femsyr/foy039](https://doi.org/10.1093/femsyr/foy039)

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Jensen, M. K. (2018). Design principles for nuclease-deficient CRISPR-based transcriptional regulators. *FEMS Yeast Research*, 18(4), [foy039]. <https://doi.org/10.1093/femsyr/foy039>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

MINIREVIEW

Design principles for nuclease-deficient CRISPR-based transcriptional regulators

Michael K. Jensen*

Novo Nordisk Foundation, Center for Biosustainability, Technical University of Denmark, Kemitorvet 220, Kgs. Lyngby 2800, Denmark

*Corresponding author: Novo Nordisk Foundation, Center for Biosustainability, Technical University of Denmark, Kemitorvet 220, Kgs. Lyngby 2800, Denmark. Tel: +45 6128 4850; E-mail: mije@biosustain.dtu.dk

One sentence summary: CRISPR technology can be used for regulating expression of genes without the use of native transcriptional regulators.

Editor: Jens Nielsen

ABSTRACT

The engineering of Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)-CRISPR-associated proteins continues to expand the toolkit available for genome editing, reprogramming gene regulation, genome visualisation and epigenetic studies of living organisms. In this review, the emerging design principles on the use of nuclease-deficient CRISPR-based reprogramming of gene expression will be presented. The review will focus on the designs implemented in yeast both at the level of CRISPR proteins and guide RNA (gRNA), but will lend due credits to the seminal studies performed in other species where relevant. In addition to design principles, this review also highlights applications benefitting from the use of CRISPR-mediated transcriptional regulation and discusses the future directions to further expand the toolkit for nuclease-deficient reprogramming of genomes. As such, this review should be of general interest for experimentalists to get familiarised with the parameters underlying the power of reprogramming genomic functions by use of nuclease-deficient CRISPR technologies.

Keywords: CRISPR; dCas9; transcriptional regulation; gRNA; scRNA; dCpf1

INTRODUCTION

Living cells regulate gene expression through coordinated actions of DNA-binding transcriptional regulators, RNA polymerases and an arsenal of auxiliary co-activators (Hahn 2004). The complex network of the transcriptional machinery controls essential functions, such as cell differentiation, cell division, responses to environmental conditions and metabolism. Our mechanistic understanding of the genes and pathways corroborating the timely and adequate execution of these essential functions have largely relied on functional genomics studies, often accommodated by efficient methodologies for accurate control of gene expression perturbations (Khalil et al. 2012; Si et al. 2015).

RNA interference, a post-transcriptional gene-silencing mechanism triggered by small-interfering RNAs or short hairpin RNAs formed from RNase III endonuclease-mediated degradation of double-stranded RNAs is one such methodology (Drinnenberg et al. 2009). By the use of iterative RNAi, knockdown of multiple genes related to chemical tolerance and production of heterologous metabolites have been optimised in microbes (Crook, Schmitz and Alper 2013; Si et al. 2015). Another method used to alter the expression of hundreds of genes, termed global transcription machinery engineering (gTME), relies on introducing mutant libraries of general transcription factors regulating promoter specificity and then screen for defined phenotypes followed by characterisation and validation of the mutant context of the transcription factor and transcriptome analysis (Alper et al. 2006). Moreover, for targeted

Received: 1 December 2017; Accepted: 6 April 2018

© FEMS 2018. This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited. For commercial re-use, please contact journals.permissions@oup.com

gene regulation, bottom-up engineering of synthetic transcription factors based upon hybrid zinc finger (ZFs) proteins and promoters for orthogonal control of gene expression has elucidated the parameters of importance for coordinated, tuned and spatial regulation of gene expression (Khalil et al. 2012). Taken together, the development of techniques for conditional loss-of-function studies by expression perturbations of multiple genes has proven to be important for our understanding of gene function, especially when studying the function of essential genes, and polygenic traits (e.g. chemical tolerance). However, though the above-mentioned methods support the simple targeting of multiple genes for knockdown and overexpression, drawbacks are evident. This includes lack of specificity and limited regulatory potential (RNAi), the need to introduce synthetic genomic material (ZFs) or the need for a screening system to select for global transcriptional changes not imagined *a priori* (gTME).

Since 2013, the bacterial Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)–Cas system has inspired the rational development of orthogonal synthetic transcriptional reprogramming strategies founded upon RNA-mediated targeting of nuclease-deficient Cas proteins to predefined genomic loci (Larson et al. 2013; Qi et al. 2013). In brief, CRISPR–Cas systems are founded on an ancient bacterial adaptive immune system in which the CRISPR-associated protein (Cas) is guided to genomic loci by a guide RNA (gRNA) with 20 nt sequence complementarity to the genomic target site (Jinek et al. 2012; Cong et al. 2013). From this platform, two basic systems have emerged for (i) genome editing by the use of gRNA-directed endonuclease-mediated DNA double-strand breaks (DSB) to assist both gene knockin and knockout (Jinek et al. 2012; Cong et al. 2013), and (ii) nuclease-deficient dCas-mediated transcriptional and post-transcriptional regulation, elucidation of epigenetic landscapes and DSB-deficient base editing to name a few (Qi et al. 2013; Lenstra et al. 2015; Fu et al. 2016; Nishida et al. 2016; Cox et al. 2017). In terms of transcriptional regulation, the nuclease-deficient forms of the type II CRISPR-associated protein Cas9, termed dCas9, from *Streptococcus pyogenes*, has been acknowledged as a potent platform for reprogramming gene expression and genomic function. Basically, dCas9 is a Cas9 mutant which have had its nuclease activity ablated by mutations in the RuvC and HNH nuclease domains, while still maintaining DNA-binding proficiency as programmed by gRNAs (Qi et al. 2013). Initially, it was demonstrated that dCas9 and a gRNA could mediate efficient gene repression in bacteria when dCas9 was guided to promoter proximal positions downstream the transcription start site (TSS), a mechanism coined CRISPR interference (CRISPRi) (Larson et al. 2013; Qi et al. 2013).

In more recent years, it has become evident that compared with the above-mentioned conventional approaches for reprogramming genome function through non-native transcriptional regulators, nuclease-deficient variants of Cas9, and *Lachnospiraceae* bacterium ND2006 Cpf1 are potent RNA-guided technologies for genome regulation in yeast. Specifically, the convenience, specificity, robustness and scalability for endogenous gene activation and repression has been widely adopted (Farzadfard, Perli and Lu 2013; Gilbert et al. 2013; Zalatan et al. 2015; Lian et al. 2017). Additionally, CRISPR-mediated transcriptional regulation is a powerful approach for targeted, combinatorial and tunable transcriptional reprogramming interface, especially considering the ease of synthesising and expressing gRNAs without time-intensive genetic modification of host genomes of species recalcitrant to transformation and targeted genome editing.

In this review, the tremendous progress of CRISPR-mediated systems applied for reprogramming transcriptional regulation in yeast will be reviewed, including the expansive list of factors that influence gRNA efficacy, and the design principles for optimal reconfiguration of dCas9 and dCpf1. At the end of the review, future perspectives on the use of nuclease-deficient Cas proteins in combination with other complementary emerging technologies for reprogramming genome functions without the need for exogenous nuclease activity will be highlighted. While this review will focus mostly on dCas9-mediated reprogramming of gene expression in yeast, a more host-agnostic review on nuclease-deficient CRISPR–dCas technologies has also recently been published (Mitsunobu et al. 2017).

CRISPR-BASED TRANSCRIPTIONAL REGULATION

Modulation of dCas9 activity

Regulation of CRISPR protein activity by protein fusions

Transcriptional regulators are by design globular. Most often regulators include two modular domains enabling (i) DNA binding and (ii) a regulatory domain supporting transcriptional activation or repression (Jensen et al. 2010; Khalil et al. 2012). Due to this modularity, domain-swapping experiments have proven successful for the generation of synthetic transcriptional regulators with defined DNA-binding specificities fused to various regulatory domains in order to potentiate transcriptional activation or repression of both native and synthetic promoters (Khalil et al. 2012; Folcher et al. 2013). The modularity of the regulatory domains has allowed the design of transcriptional regulators which can regulate gene expression to much higher levels compared to regulators only relying on the native design (Folcher et al. 2013).

When nuclease-deficient dCas9 was initially used in bacteria, gene repression by up to 99.9% was reported (Qi et al. 2013). However, when using only dCas9 and a single gRNA in yeast to target gene expression regulation, only modest repressions ranging from no effect to 2–3-fold repressions have been reported (Farzadfard, Perli and Lu 2013; Deaner, Mejia and Alper 2017; Vanegas, Lehka and Mortensen 2017), although a single study has reported up to 18-fold downregulation of reporter gene activity (Gilbert et al. 2013). This level of regulation is comparable to studies in other eukaryotes, and suggest that the single gRNA complex with dCas9 is not sufficient for sterically hindering RNA progression and/or blocking of transcription initiation (Gilbert et al. 2013; Lawhorn, Ferreira and Wang 2014). Inspired by the modular design of other synthetic transcriptional regulators, and acknowledging that gRNA-bound CRISPR proteins are analogous to simple DNA-binding moieties, studies using dCas9- or dCpf1-mediated expression perturbations nowadays therefore include additional regulatory domains fused to dCas9 and/or dCpf1 in order to improve repression and activation potentials (Fig. 1a and b).

In their seminal study on dCas9-mediated transcriptional regulation in eukaryotes, Gilbert et al. compared the effect of fusing the mammalian transcriptional repressor domain, Mxi1, reported to interact with the chromatin modifying histone deacetylase Sin3 homolog in yeast, to dCas9 (Schreiber-Agus et al. 1995; Gilbert et al. 2013) (Fig. 1a). Targeting the *TEF1* promoter, dCas9–Mxi1 repressed reporter gene activity by 53-fold compared to the above-mentioned 18-fold using only dCas9. This finding is comparable to the effect recently reported in *Yarrowia lipolytica* (Schwartz et al. 2017). Here, Schwartz et al.

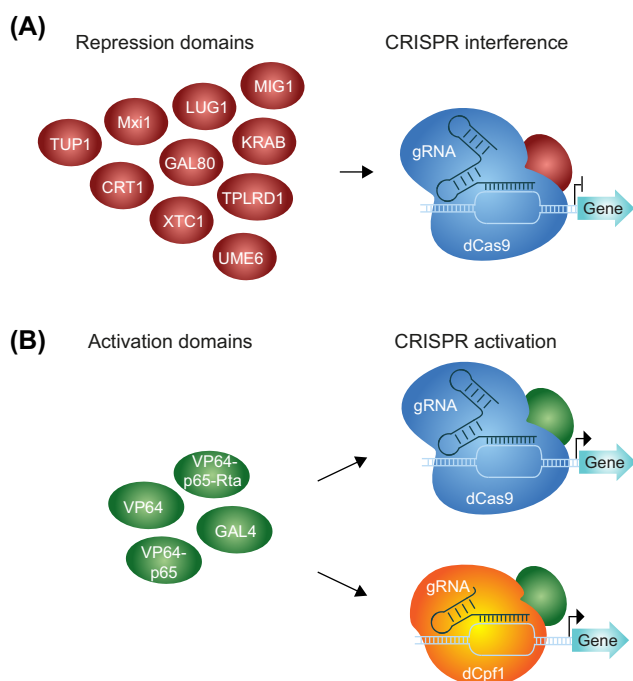


Figure 1. Modulation of nuclease-deficient Cas9 and Cpf1 activities in yeast by fusion of transcription regulatory domains. (a) Schematic illustration of the transcriptional repression domains which have been successfully fused to nuclease-deficient dCas9 CRISPR activation in yeast. (b) Schematic illustration of the transcriptional activation domains which have been successfully fused to nuclease-deficient dCas9 and dCpf1 for CRISPR activation in yeast.

reported up to 10-fold repression of *MIH1* transcript levels when using dCas9, yet when directly comparing the effects of using dCas9 versus dCas9-Mxi1 on the *Ku70* and *Ku80* genes, related to non-homologous end joining, Schwartz et al. observed the highest level of repression (87%) for *Ku80* when the dCas9-Mxi1 fusion was compared to dCas9 (38%) (Schwartz et al. 2017). To further investigate dCas9 fusion designs for optimal repression, Schwartz et al. and Gander et al. (Gander et al. 2017) also tested fusions between dCas9 and the Krüppel-associated box (or KRAB domain) from tetrapod vertebrate genomes (Witzgall et al. 1994). Here Schwartz et al. found comparable levels of transcript abundances in the order of 2–3-fold repression for dCas9-KRAB as also observed for dCas9, while Gander et al. observed ~2.5-fold repression for dCas9-KRAB compared to ~12-fold when using dCas9-Mxi1 to control the expression of a synthetic *CYC1*-based promoter (Gander et al. 2017). These findings are also corroborated by mathematical models predicting that repression via dCas9 alone leaks more than repression via dCas9-Mxi1 (Gander et al. 2017). In addition to Mxi1 and KRAB, Gander et al. also tested repression domains GAL80, LUG, TPLRD1, TUP1 and XTC1 (Flick and Johnston 1990; Edmondson, Smith and Roth 1996; Wu et al. 2001; Traven et al. 2002; Pierre-Jerome et al. 2014), with LUG and TPLRD1 showing similar repressing potential as KRAB, while neither GAL80, TUP1 and XTC1 fusions showed any repression (Fig. 1a). Similarly, Lian et al. (2017) tested variants of repressor domains TUP1, MIG1, CRT1, XTC1 and UME6 (Edmondson, Smith and Roth 1996; Ostling, Carlberg and Ronne 1996; Kadosh and Struhl 1997; Zhang and Reese 2005; Traven et al. 2002), and reported a tri-partite repression domain engineered from UME6, MIG1 and TUP1 to be the most successful design for dCas9-mediated repression (up to 5-fold stronger repression compared to dCas9-Mxi1), whereas fusions to dCpf1 was not effective for CRISPRi (Lian et al. 2017).

In addition to fusion of repressor domains, several studies have worked on fusing CRISPR proteins with single and multiple transcriptional activation domains to allow for CRISPR-mediated gene expression activation, termed CRISPRa (Gilbert et al. 2014). In yeast, Farzadfard et al. were the first to show that dCas9 could be used as a transcriptional activator when fused to an activation domain (Farzadfard, Perli and Lu 2013). Here, they initially tested dCas9-VP64 guided to either sense or antisense strand of the minimal *CYC1* promoter and found several positions of gRNAs enabling statistical significant upregulation of reporter fluorescence in the order of 1.5–3.0-fold (Farzadfard, Perli and Lu 2013). Similar fold changes have been observed for dCas9-VP64 targeting the *GAL1* and *ADE2* promoters (Farzadfard, Perli and Lu 2013; Vanegas, Lehka and Mortensen 2017), while Naranjo et al. reported >100- and >250-fold increases in transcript levels when using dCas9-VP64 and *GAL4*-dCas9-VP64, respectively, to target *FRM2* (Naranjo et al. 2015). Contrastingly, dCas9 did not increase reporter gene activity when guided by any of the tested gRNAs. In addition to testing dCas9-VP64 for CRISPRa, Farzadfard et al. also tested the potential of guiding multiple copies of dCas9-VP64 and thereby tune reporter promoter activity. From this, the authors observed that reporter gene activity increased by up to 70-fold when targeting dCas9-VP64 to a maximum of 12 identical operator positions using a single gRNA (Farzadfard, Perli and Lu 2013). One interesting observation, acknowledged already at this early stage of CRISPR-mediated transcriptional reprogramming, was the strong influence exerted by the position of the gRNA relative to the impact dCas9-based regulation. Specifically, Farzadfard et al. found that although dCas9-VP64 could serve as a transcriptional activator when gRNAs were positioned upstream of the TATA box, significant repression of reporter gene activity in the order of 2–3-fold was observed when the fusion protein was guided to positions overlapping or downstream of the TATA box (Farzadfard, Perli and Lu 2013). The gRNA positions-specific effects will be covered in more detail in section ‘Modulation of gRNA activity’.

In addition to single-domain VP64, CRISPR proteins have also more recently been successfully fused to combinations of transcriptional activators, including the VPR, which is constructed from quadruple copies of the Herpes simplex viral protein (VP16), the transactivation domain of NF- κ B p65 subunit (p65AD) and the Epstein-Barr virus R transactivator (Rta) (Chavez et al. 2016; Deaner and Alper 2017; Jensen et al. 2017). As evidenced by Chavez et al. comparing reporter gene expression levels using gRNAs targeting the yeast *GAL7* and *HED1* promoters, dCas9-VPR mediated ~100- and 40-fold upregulation, respectively, compared to the modest 14- and 8-fold increases observed when guiding dCas9-VP64 (Fig. 1b) (Chavez et al. 2015). Beyond the use of nuclease-deficient Cas9 from *S. pyogenes*, Lian et al. systematically tested novel CRISPR-mediated transcriptional activators by fusing several nuclease-deficient CRISPR proteins to activation domains (Lian et al. 2017). Here, the authors found that the optimal activation domain was dependent on the Cas protein tested with the best-performing *S. pyogenes* dCas9 variant showing up to 12-fold activation of reporter gene activity when fused to VPR, while the best-performing dCpf1 variant induced up to 8-fold activation of gene activity when fused to VP64-p65AD (Lian et al. 2017).

Acknowledging the findings from dCas9 fusion studies, several groups have since then successfully applied dCas9-VPR for CRISPRa in yeast (Deaner and Alper 2017; Deaner, Mejia and Alper 2017; Jensen et al. 2017). Even though most upregulations observed are in the 2–10-fold range, Deaner et al. observed more than 160-fold changes in *NDE2* gene expression when

comparing the best gRNA position for mediating CRISPRi using dCas9-Mxi1 versus the most potent gRNA position for mediating CRISPRa using dCas9-VPR (Deaner and Alper 2017). In alignment with the findings from Farzadfard et al., Deaner and Alper also reported the position-specific potential of dCas9-VPR to modestly repress gene expression (Farzadfard, Perli and Lu 2013; Deaner and Alper 2017).

Taken together, several studies have reported CRISPRi/a in yeast yielding changes in gene expression and activity in the order of >50-fold downregulation and >100-fold upregulation, with dCas9-Mxi1 and dCas9-VPR currently being the most often adopted regulators. In general, dCas9 is a versatile fusion partner for both activation and repression domains, yet the optimal choice of regulatory domain(s) to be used for transcriptional reprogramming can depend on the CRISPR protein. This opens up opportunities for multifunctional CRISPR-mediated reprogramming using orthogonal PAM sequences of different CRISPR proteins as analogs for upstream activating (UAS) or repressing sequences (Lian et al. 2017).

Regulating expression of genes encoding CRISPR proteins

When using nuclease-deficient CRISPR-based synthetic regulators, it is important to acknowledge that the regulatory potential of transcriptional regulators inherently depend on the expression level of the transcriptional regulator itself, with higher expression most often providing the highest repression and/or activation level of the target gene(s) in question (Skjoedt et al. 2016). In line with this, most studies in yeast make use of strong constitutive or glycolytic promoters to drive the expression of the gene encoding dCas9 and variants thereof (Gilbert et al. 2013; Lian et al. 2017). From *S. cerevisiae*, this includes the *TDH3* (or *GDP1*), *TEF1* and *PDC1* promoters for use in *S. cerevisiae* and *Kluyveromyces marxianus* (Gilbert et al. 2013; Chavez et al. 2015; Smith et al. 2016; Nambu-Nishida et al. 2017), whereas in *Y. lipolytica* Schwartz et al. used a previously engineered strong constitutive promoter based on a truncated core *TEF1* promoter fused to eight copies of a 105-bp UAS element from the *TRX2* promoter, named pUAS1B8-TEF(136), to drive the expression of dCas9 (Blanchin-Roland, Cordero Otero and Gaillardin 1994; Blazeck et al. 2011; Schwartz et al. 2016; Schwartz et al. 2017).

In addition to constitutive expression of dCas9, the ability to program the onset of target gene regulation has prompted the use of inducible expression of dCas9 for conditional transcriptional reprogramming in yeast. By the use of a synthetic promoter originally developed by Ellis et al., galactose- and anhydrotetracycline-inducible (aTc) expression of dCas9-VP64 was achieved (Ellis, Wang and Collins 2009; Farzadfard, Perli and Lu 2013), allowing for 70-fold inducible expression of a minimal *CYC1* promoter with outputs comparable to the activation potential of other commonly used endogenous *GAL1* and *CUP1* promoters (Farzadfard, Perli and Lu 2013). Together with the complementary set of light- and allosterically regulated CRISPR/Cas9 systems reported in mammalian cells (Gao et al. 2016; Oakes et al. 2016), such galactose- and aTc-inducible expression of dCas9 and its variants allows control over the onset of target gene expression.

Modulation of gRNA activity

Recruitment of effectors by aptamer-fused gRNAs

The inherent one-to-one relationship between dCas9 and the gRNA constrains dCas9-mediated programming of multigene transcription-based gene circuits to only one direction of regulation (i.e. repression or activation) at the single-cell level. This

is not levelling the complexity and sophistication underpinning native transcriptional networks. However, in analogy to the fusion of regulatory domains to dCas9, the engineering of the gRNA itself has proven a modular and tunable platform for diversifying not only the genomic target sites (seed sequence), but also the function of CRISPR-mediated transcriptional regulation.

Taking advantage of the 3'-end of gRNAs, Zalatan et al. and Kiani et al. were the first to engineer gRNAs with protein-interacting RNA aptamers (Kiani et al. 2015; Zalatan et al. 2015). In yeast, this included gRNAs which indeed could control not only localisation of dCas9 (and Cas9), but also function. In their seminal studies, they showed that fusing RNA aptamers to the tracr-part of gRNAs enabled binding of RNA-binding proteins and thereby control of regulatory potential depending on the protein-interaction partner anchored to the RNA-binding protein (Fig. 2a) (Kiani et al. 2015; Zalatan et al. 2015). More specifically, in order to refactor both target sequence specificity and function into these scaffolding RNAs (scRNAs), Zalatan et al. tested (i) different aptamers, (ii) 5'- versus 3'-end fusions, (iii) different numbers of aptamers, (iv) linker length between gRNA 5'-end and aptamer, and (v) orthogonality between aptamer and their cognate RNA binding interaction partners. The systematic characterisation uncovered three potent RNA-binding modules each consisting of the aptamer and its RNA-binding protein partner fused to either a VP64 activation domain or an Mxi1 repression domain (Fig. 2a). Moreover, the authors showed that several aptamers could be introduced into single scRNAs and no crosstalk was observed between the components of the RNA-binding modules, ultimately enabling both dCas9-mediated activation and regulation in single cells only depending on the seed sequence and aptamer encoded in the scRNA(s) (Zalatan et al. 2015). Most importantly, when using the scRNA strategy together with VP64-based RNA-binding modules in yeast more than 50-fold activation of a synthetic reporter promoter was observed, compared to modest 2–3-fold activation observed for dCas9-VP64. Using two different scRNAs for targeted gene activation together with dCas9-mediated repression, Zalatan et al. enabled synthetic control over branchpoint fluxes in the violacein biosynthetic pathway (Fig. 2b), while Jensen et al. demonstrated combinatorial reprogramming of mevalonate and carotenoid pathway genes using the MCP:VPR activation and PCP:Mxi1 repression modules, ultimately enabling significant changes in carotenoid levels (Fig. 2c) (Zalatan et al. 2015; Jensen et al. 2017).

In summary, the engineering of gRNAs into scRNAs offer CRISPR-based multidirectional reprogramming of gene expressions, and is of particular relevance for studying, and improving our understanding of, polygenic traits and combined effects of key metabolic pathway branch points.

Regulating gRNA expression

The expression levels of gRNAs have been shown to correlate with CRISPR/Cas9-mediated genome engineering efficiency in mammalian cells (Hsu et al. 2013). To match the stoichiometries of dCas9 or dCpf1 expressed from strong constitutive polymerase II promoters (see section 'Regulating expression of genes encoding CRISPR proteins'), optimising the expression of gRNA and scRNAs has been investigated vigorously. In general, polymerase III promoters are used to drive expression of gRNAs because RNA polymerase II promoters add extra nucleotides to the 5'- and 3'-ends of gRNAs, and thereby are believed to interrupt gRNA function (Yoshioka et al. 2015). Originally, the polymerase III promoters *SNR52* and *RPR1* were adopted for constitutive delivery of gRNAs in yeast (Fig. 3) (DiCarlo et al. 2013; Farzadfard, Perli and Lu 2013; Gilbert et al. 2013). Especially, the use of *SNR52*

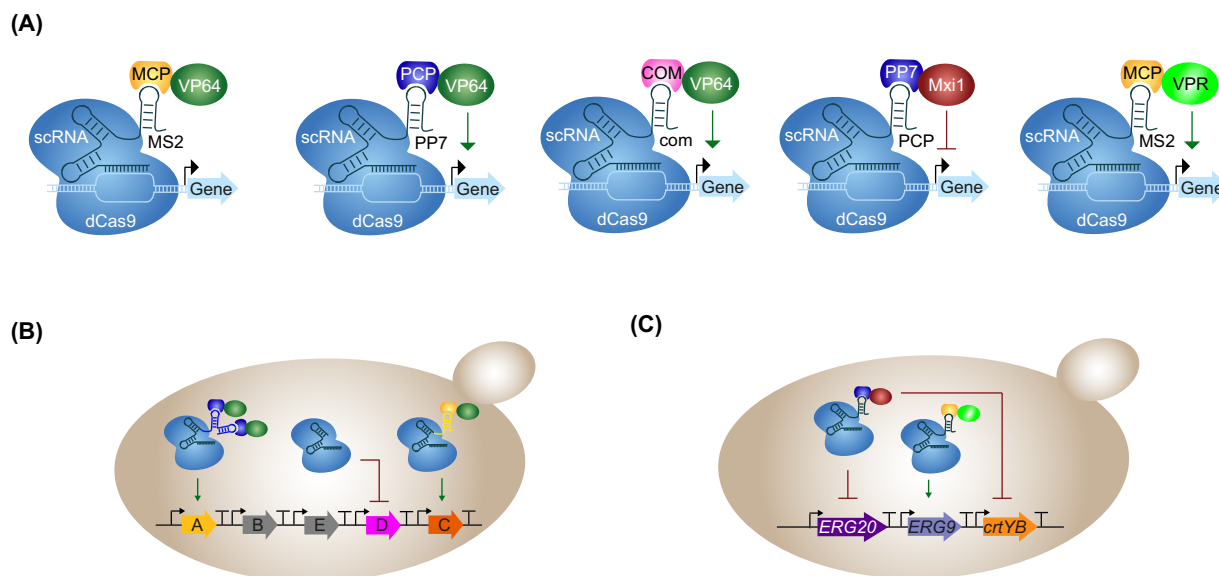


Figure 2. Design and application of scaffold RNAs controlling both genomic target sequence and regulatory function. (a) Five examples of scaffold RNAs (scRNAs) used in yeast. ScRNAs are engineered gRNAs with protein-interacting RNA aptamers. The protein and aptamer are collectively referred to RNA-binding modules. The aptamer-binding protein MCP, PCP and COM interact in an orthogonal manner with the aptamers MS2, PP7 and com, respectively. MCP, PCP and COM can be fused to activation or repression domains, thereby enabling scRNAs to specify genome target locus and regulatory function. (b) An example illustrating single-cell reprogramming of the expression of three genes encoding part of the violacein biosynthetic pathway. (c) An example illustrating single-cell reprogramming of the expression of three genes encoding proteins regulating metabolic flux through the mevalonate and carotenoid pathways.

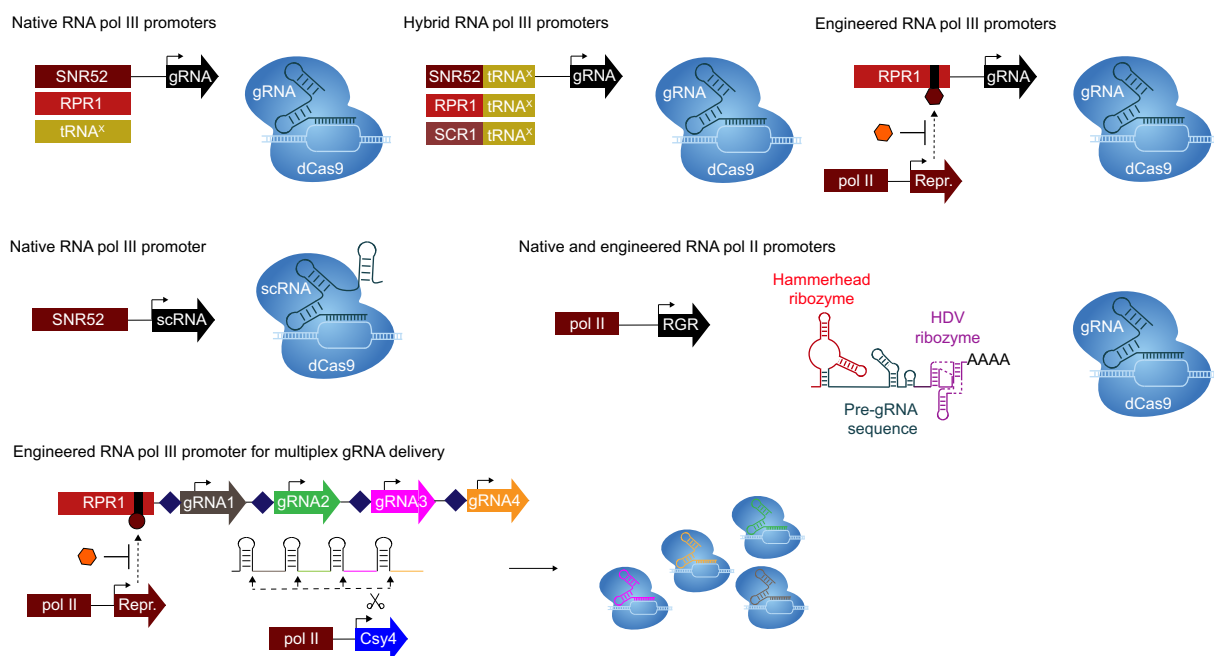


Figure 3. Expression of guide RNAs (gRNAs), scaffold RNAs (scRNAs), and ribozyme-flanked gRNAs. Examples of native, hybrid and engineered promoters reported to drive the expression of gRNAs, scRNAs, and ribozyme-flanked gRNAs in yeasts.

promoter has been used extensively because of its native transcript cleavage sites that result in the excision of gRNAs from the primary transcripts (DiCarlo et al. 2013). Next, to enable larger flexibility to the design and expression strength of gRNAs, two studies immediately following the aforementioned studies on constitutive delivery of gRNAs tested the fusion of self-cleaving hepatitis delta virus (HDV) and hammerhead-type ribozymes to the gRNA, thereby enabling genome editing derived from polymerase II promoters (Gao and Zhao 2014; Ryan et al. 2014). Gao

and Zhao were the first to highlight the use of ribozyme-flanked gRNAs to enable use of pol II promoters to drive expression of pre-gRNAs targeted for self-catalysed processing (Fig. 3) (Gao and Zhao 2014; Zhang et al. 2017). In addition to that study using the ADH1 pol II promoter to drive the expression of gRNAs flanked by a 5' minimal hammerhead and a 3' HDV ribozymes at the 5' and 3' ends, respectively, Ryan et al. tested a total of eleven pol III promoters for delivery of functional gRNAs (Ryan et al. 2014). The study concluded that while tRNA promoters

were compatible with the HDV ribozyme fusion yielding nearly 100% engineering efficiency, the snoRNA promoter SNR52 was the only non-tRNA promoter levelling such efficiencies when fused to the HDV ribozyme (Ryan et al. 2014). These findings add to the more recent benchmark of synthetic pol III fusion promoters, pol II promoters (driving expression of ribozyme-flanked gRNAs (RGRs)), and non-tRNA pol III promoters driving expression of gRNAs in *S. cerevisiae* and *Y. lipolytica* (Fig. 3) (Schwartz et al. 2016; Deaner, Mejia and Alper 2017). Here, expression levels were found to largely correlate with the engineering efficiency of the various designs, with the synthetic fusion promoters between truncated pol III promoters and tRNA promoters yielding the highest scores (>90%) in *Y. lipolytica*, while the strong pol II TEF1-RGR approach produced almost 4-fold more gRNA compared to SNR52 correlating with a stronger regulatory potential as well (Schwartz et al. 2016; Deaner, Mejia and Alper 2017). Also, Gander et al. used the minimal CYC1 promoter to build a set of gRNA-responsive polymerase II promoters (pGRR) driving the expression of RGRs (Gander et al. 2017). In their study, a library of 400 dual-target site pGRRs were constructed together with 20 RGRs totalling 8000 NOR (either one or both) logic gates, including both constitutive and estradiol inducible pol II promoters to drive the expression of RGRs, ultimately yielding up to 12-fold regulation from single gRNA controlled reporter promoters (McIsaac et al. 2013; Gander et al. 2017).

Apart from native pol III and inducible pol II promoters controlling the expression of gRNAs and RGRs, other groups have made use of an engineered native RPR1 pol III promoter to include a TetO binding site for a Tc-inducible depression of gRNA expression when co-expressing the constitutively expressed TetR repressor thereby enabling expression perturbations in the order of 2–20-fold (Fig. 3) (Farzadfard et al. 2013; Smith et al. 2016; Jensen et al. 2017; Ferreira et al. 2018). Interestingly, in the study by Ferreira et al., three gRNA cassettes were expressed from a single engineered RPR1 pol III promoter, and subsequently the Csy4 endoribonuclease was used to digest the transcript into subelements and boost dCas9-VP64-mediated expression of HMG1, OLE1 and ACS1 promoters ~2-fold (Ferreira et al. 2018). This elegant approach easily circumvents the need for reuse of the same promoter, or the need for multiple different promoters, when aiming to reprogram transcription of multiple genes (Fig. 3).

In summary, though native pol III promoters were originally the design of choice, the simple engineering of pol II promoters driving the expression of self-cleaving RGRs allows for control of genome reprogramming founded on basically any pol II promoter has gained attention (Zhang et al. 2017). Also, the sterical hindrance offered by inducible repressors can be used to engineer pol III promoters for functional, timely and potent gRNA delivery.

Multiple gRNAs for reprogramming of genomic functions

Regulating native and synthetic promoters by the use of endogenous or engineered transcription factors is dependent on their ability to bind cognate TF-binding sites in such promoters (Khalil et al. 2012). In analogy to this, and as mentioned earlier (section 'Regulating expression of genes encoding CRISPR proteins'), Farzadfard et al. showed that synergistic effects on transcriptional regulation can be observed when using multiple gRNAs directing dCas9-mediated control of target promoters. For instance, two separate gRNAs conferred each 2-fold repression, whereas a combination of the two showed 7-fold repression. Moreover, Farzadfard et al. also tested the guiding of multiple copies of dCas9-VP64 and thereby tune reporter pro-

motor activity, and hereby observed that reporter gene activity increased by up to 70-fold when targeting dCas9-VP64 to a maximum of 12 positions (Farzadfard, Perli and Lu 2013). Likewise, Gilbert et al. tested 7 × gRNAs on TetO promoter showing the highest ever reported repression in reporter gene activity by the use of dCas9-Mxi1 (153 ×, Fig. 1), while Deaner et al. used dual gRNAs expressed from both SNR52- and TEF1-derived promoters to boost the regulatory potential of dCas9-VP64 (Gilbert et al. 2013; Deaner, Mejia and Alper 2017). Contrastingly, Schwartz et al. also used two gRNAs in the –120 bp TSS region to test if this enhanced repression of Ku70 and Ku80, yet they found only marginal effects from using two gRNAs compared to the perturbations observed when only using one gRNA (Schwartz et al. 2017).

Taken together, as in native and other synthetic transcription regulatory networks, the number of regulators tethered to the target regulon offers a modular valve to tune the impact of CRISPR-dCas9-mediated reprogramming. However, the use of multiple gRNAs should be carefully designed with particular focus on the position of existing regulatory elements and nucleosomes in order to tune regulatory potential by simple increases in gRNA numbers targeting such regions (see sections 'Position effects of gRNAs' and 'Nucleosome positioning and chromatin accessibility').

Strand-bias versus regulatory potential

The mechanistic understanding of CRISPRi in relation to gRNA positioning has attracted a lot of attention. Initially, the underlying mechanism of dCas9-mediated transcriptional repression was elucidated using NET-seq in *Escherichia coli* (Churchman and Weissman 2011; Qi et al. 2013). In *E. coli*, Qi et al. identified that gRNAs induced strong transcriptional pausing upstream of the gRNA target locus on the non-template strand, leading to the hypothesis that physical collision between the elongating RNA polymerase and the dCas9:gRNA complex conferred a transcriptional block (Qi et al. 2013). In yeast, however, Farzadfard et al. were the first to show that placing gRNAs at similar positions downstream TSS, but on different strands of a promoter, had similar negative effects on gene expression. Moreover, placing the gRNAs on either strand upstream the TATA box and the TSS leads to similar dCas9-VP64-mediated gene activation (Farzadfard, Perli and Lu 2013). Likewise, Gilbert et al. later reported that the targeted DNA strand and guanine-cytosine content of gRNA were not determining factors for successful CRISPRi in their study (Gilbert et al. 2014). Finally, in a more recent study, adopting a much larger gRNA library approach to deduce chemical-genetic interaction, Smith et al. designed 383 gRNAs to the +500 bp to –500 bp of the TSS region window of five genes (Smith et al. 2016). Here, the authors found no strand-bias in relation to gRNA efficacy along the 1 kb window tested.

In line with these findings, it has recently been further elucidated that, in contrast to the findings from CRISPRi in *E. coli* (Qi et al. 2013), dCas9 in yeast may not act as a simple transcriptional road-block mechanism for the RNA polymerase in a strand-specific manner, but rather that the gRNA:dCas9 complex supports the formation of a permissive transcript formations, including premature termination and formation of novel transcript, in both sense and antisense orientation (Howe et al. 2017). Taken together, this highlights that not only is yeast recalcitrant to potential CRISPRi strand-bias, but also that conclusions drawn from CRISPRi studies should consider the integrity of the transcripts targeted.

Position effects of gRNAs

In contrast to studies on potential strand-specific effects, there is much stronger evidence from bigger data sets on the position-specific effects of gRNAs in promoters.

In general, gRNAs targeting the region upstream of the TATA box and TSS have largely correlated with both dCas9-VP64- and dCas9-VPR-mediated gene activation, while positioning dCas9 variants downstream of, or in close proximity to, TATA boxes negatively impacts gene expression (Farzadfard, Perli and Lu 2013; Deaner and Alper 2017). For instance, targeting of dCas9-VP64 to a position upstream the TATA box provided almost 5-fold upregulation of a minimal GAL1 promoter, while targeting gRNAs to the TATA box or the kozak element downstream thereof led to CRISPRi, likely due to interference with the transcriptional initiation complex, as also observed by Deaner et al. when using dCas9-VPR for CRISPRi (Fig. 1) (Farzadfard, Perli and Lu 2013; Deaner, Mejia and Alper 2017). Moreover, Deaner and Alper provided a detailed study on the systematic testing of enzyme perturbation sensitivities (STEPS) by positioning gRNAs in an ~0–750 bp window upstream the TATA box of various native yeast promoters. By observing changes in gene expression as dCas9-Mxi1 is positioned further away from the TATA box and dCas9-VPR is positioned closer towards the TATA box, the authors were able to infer flux sensitivity maps by plotting changes in glycerol formation as a function of the 5 genes' graded expression (Deaner and Alper 2017). Application-wise, the authors used STEPS to show that GPD1 and TPI1 gene expression levels positively and negatively correlate with glycerol titers, respectively. Ultimately, these interrogations lead to a simple overexpression strategy for GPD1/GPP1 yielding more than 5-fold increase in glycerol titers (4.89–28.0 g/L). Likewise, using STEPS on five key pentose phosphate pathway genes to increase flux through the aromatic amino acid pathway yielded ~8-fold increase in 3-DHS titers (to 126.4 g/L) in a *zwf1* deletion background (Deaner and Alper 2017).

The abovementioned studies on gRNA position effects are largely corroborated by another recent study. Here, Smith et al. used CRISPRi based on dCas9-Mxi1 to test ~1000 gRNAs directed against 20 genes whose expression levels are predicted to influence sensitivity to specific growth inhibitors (Smith et al. 2016). Here, the authors found that the median guide effect for dCas9-Mxi1 was maximal in the window of ~200 bp to TSS, while gRNAs positioned outside the ~200 bp to TSS window only in some cases could effectively repress transcription, but less effectively (Smith et al. 2016). These findings differ from the studies performed in mammalian cells in which the ~50 to +300 region relative to TSS was found to be the most impactful for CRISPRi (Gilbert et al. 2014). Still, for yeast, Smith et al. developed a tool for gRNA design (<http://lp2.github.io/yeast-crispri/>) taking into considerations both genome position, chromatin accessibility (section 'Nucleosome positioning and chromatin accessibility'), nucleosome (section 'Nucleosome positioning and chromatin accessibility'), gRNA length and sequence (section 'gRNA specificity and length'), as well as transcription factor occupancy of the target site (section 'Other features of relevance—basal promoter activity, TF-binding interference and RNA secondary structure'.). (Smith et al. 2016). Based on these findings and others, Schwartz et al. identified gRNAs for efficient repression of gene expression in *Y. lipolytica* (Schwartz et al. 2017). In the largest-to-date study, Smith et al. targeted dCas9-Mxi1-mediated repression of >1500 genes essential for growth (Smith et al. 2017). By analysing > 9000 strains containing a unique sequence-verified gRNA, the authors refined their earlier findings (Smith et al. 2016), now highlighting gRNA positions in the

region between TSS and ~125 bp upstream TSS to be particularly effective for CRISPR-mediated repression (Smith et al. 2017).

Having this said, even though Jensen et al. targeted 88 gRNAs to the ~200 bp to TSS window of 12 native yeast promoters, the authors found several gRNAs to be non-functional when using dCas9-VPR and dCas9-Mxi1 for transcriptional reprogramming (Jensen et al. 2017).

Summarising the positioning of gRNAs relative to TATA and TSS offers an easy tunable and portable strategy to perturb gene expression activity for both CRISPRi and CRISPRa, though specific positioning should also take into consideration other local sterical and regulatory features of eukaryotic promoters (see sections 'Nucleosome positioning and chromatin accessibility' and 'gRNA specificity and length').

Nucleosome positioning and chromatin accessibility

Nucleosomes have been shown to effectively interfere with the action of DNA-binding transcriptional regulators (Griesenbeck et al. 2003; Mao et al. 2011). CRISPR systems, inherently relying on DNA binding, have been used widely in the eukaryotic kingdom, but unlike bacteria, DNA in eukaryotes is largely coiled around histones to form nucleosomes, making eukaryotic DNA more tightly packaged and less accessible to other DNA-binding proteins (Rando and Chang 2009; Rando and Winston 2012). As reviewed above, gRNAs targeting the same promoter can have differences in their transcriptional impact (Smith et al. 2016), even gRNAs positioned closely can have different efficiencies not strictly correlating with their distance from TSS (Farzadfard, Perli and Lu 2013; Jensen et al. 2017; Vanegas, Lehka and Mortensen 2017). This led Smith et al. to investigate whether chromatin accessibility and nucleosome positioning could also impact a guide's efficiency for dCas9-mediated transcriptional regulation. In analogy with transcription factors canonically binding nucleosome-free DNA within promoters crucial to the regulation of gene expression, Smith et al. took advantage of the study Schep et al. recently performed in which they identified a highly structured pattern of DNA fragment lengths and positions around nucleosomes in yeast using an assay of transposase accessible chromatin (ATAC-seq). Using the ATAC-seq data together with other genome-wide nucleosome position datasets (Lee et al. 2007), Smith et al. found a positive correlation between guide efficiency and chromatin accessibility scores in the TSS -400 bp to TSS +400 bp window. Even though studies have shown that gRNA positioning downstream TSS can be effective for transcriptional reprogramming (Farzadfard, Perli and Lu 2013; Deaner and Alper 2017), Smith et al. observed from testing hundreds of gRNAs that the relationship between guide efficiency and ATAC-seq read density extended into the typically nucleosome-occupied region downstream TSS (Yuan et al. 2005; Lee et al. 2007; Zaugg and Luscombe 2012), underpinning the notion that gRNA efficacy is not *sensu stricto* determined by its TSS proximity. These observations are in line with biochemical studies showing that Cas9 and dCas9 cannot stably interact with a PAM when located in the nucleosome core, indicating PAM accessibility to be the critical determining factor for nuclease-deficient CRISPR protein activity (Hinz, Laughery and Wyrick 2015; Isaac et al. 2016), which again underpins the observation that guides which target regions of low nucleosome occupancy and high chromatin accessibility are likely to be more effective (Smith et al. 2016, 2017). Moreover, in human cells, several reports have highlighted that locations for efficacious gRNAs for dCas9-mediated transcriptional repression correlate with chromatin marks associated with active transcription and

open chromatin (H3K27ac, H3K9ac, H3K4me3, H3K4me2 and H3K79me2) (Horlbeck et al. 2016; Radzisheuskaya et al. 2016).

Taken together, biochemical and *in vivo* evidence suggest that gRNA design strategies should avoid targeting gRNAs near the nucleosome core. Moreover, since several data sets exist on large-scale nucleosome positioning and DNA accessibility maps (Jiang and Pugh 2009; Schep et al. 2015), development of future computer-aided design tools for design of specific and highly efficient gRNAs should evaluate the inclusion of such data sets when inferring gRNA selections.

gRNA specificity and length

The length of the gRNA is a crucial factor for target specificity of nuclease-proficient Cas9, with 17 nt gRNAs observed to be the minimum length for targeted nuclease activity (Fu et al. 2014b). For CRISPRi and CRISPRa, several studies have assessed the impact of truncated gRNAs compared to full-length 20 nt spacer regions of gRNAs. Initially, Qi et al. found that for CRISPRi the strongest repression was observed when using full-length gRNAs, which is corroborated by Kiani et al. who found that dCas9-mediated activation increase from 2- to 100-fold activation when seed length is shifted from 8 to 20 nt (Kiani et al. 2015). Likewise, in yeast Smith et al. have found that mismatches located in the seed region positioned 1–10 relative to the PAM were poorly tolerated by both full-length and truncated gRNAs (Smith et al. 2016), which is also in agreement with findings from Cas9-targeting *in vitro* and in mammalian cells (Hsu et al. 2013; Wu et al. 2014; Fu et al. 2014a), and the observation that as little as a single base-pair mismatch is sufficient to redirect dCas9 targeting in yeast (Farzadfard, Perli and Lu 2013).

In general, the conclusions drawn from these studies suggest that truncating gRNAs reduce the efficacy of CRISPR-dCas9-mediated transcriptional regulation towards both perfectly matched and imperfectly matched target sequences compared to 20 nt full-length gRNAs (Kiani et al. 2015; Smith et al. 2016), though there is some degree of flexibility in the design of the seed-distal positions of gRNAs which may be considered when designing gRNAs targeting promoter regions dense in nucleosomes and upstream-activating sequences.

Other features of relevance—basal promoter activity, TF-binding interference and RNA secondary structure

In the previous sections, some design principles stand out as being of particular importance for efficient CRISPR-mediated transcriptional reprogramming. For gRNAs, this includes (i) the positive correlation between gRNA expression level and engineering efficiency (Schwartz et al. 2016; Deaner et al. 2017), (ii) targeting of gRNAs to the window between –125 bp upstream TSS and TSS for CRISPRi, and (iii) positioning of gRNAs in nucleosome-depleted regions of target promoters (Smith et al. 2016, 2017). In addition to these design criteria, a few additional studies deserve to be mentioned for designing optimal CRISPR-mediated probing of genome function.

First, when selecting genes of interest it is worth considering the observed inverse relationship between basal expression levels of the genes of interest and the relative expression perturbations which can be gained by dCas9-mediated reprogramming (i.e. high basal expression can often only be marginally activated and vice versa) (Chavez et al. 2015; Jensen et al. 2017). In line with this, another factor of interest is related to the regulatory organisation of the targeted promoter(s). On the use of dCas9 to block the DNA binding of the synthetic transcriptional regulator rTA on the synthetic TetON-Venus reporter promoter, Gilbert et al. found that a 115-fold repression of rTA-induced activation

can be obtained when co-expressing dCas9 and gRNA, suggesting that dCas9 can sterically compete with transcription factors otherwise controlling the regulation of the target promoter, indicating that CRISPRi and CRISPRa can be used to identify regulatory functions of upstream-activating and upstream-repressive sequences (Gilbert et al. 2013). However, from their large-scale library approach, Smith et al. (2016) only found a small number of cases where overlap with a transcriptional activator binding site correlated with increased CRISPRi efficacy, indicating that this design parameter may be subject to the native regulatory context of the targeted promoters. In relation to this, Jensen et al. showed CRISPR-mediated up- and downregulation of gene activity of *OLE1* over the course of 48 h, correlating with time-resolved quantitative analysis demonstrating that *OLE1* is highly expressed during early-phase to mid-exponential phase and downregulated from late exponential phase (Jensen et al. 2017). Finally, another important gRNA design principle to mention comes from the before-mentioned large-scale CRISPRi study performed by Smith et al. (2017). Here, the authors identified a significant correlation between the folding energy in kCal/mol for the predicted RNA structure (leader, 20 nt gRNA targeting sequence and structural part) of the gRNA and the gRNA efficacy (i.e. more folding, less efficacy) (Smith et al. 2017).

Taken together, numerous design parameters have been elucidated for optimal CRISPR-mediated transcriptional regulation. Several of the parameters are defined from large-scale studies and considered to be gene-inspecific. Likewise, as evident from several studies, CRISPR-mediated regulatory potential of target promoters can be sustained over long time spans (Deaner and Alper 2017; Jensen et al. 2017), highlighting the robustness and orthogonality of the technology.

OUTLOOK

As is evident from the previous sections, there are many design considerations to be taken into account when using CRISPR to probe genome functions through CRISPRi and CRISPRa. Still, for transcription perturbations, compared to other methods such as RNAi, gTEM and targeted overexpression, CRISPRi/a offer easy design, programmable RNA-mediated targeting and regulatory direction of both individual and multiple genes at the single cell level. This is powerful and leverages the nature of multifactorial native transcriptional regulation for transcription perturbations. Indeed, for transcriptional reprogramming, dCas9-based approaches have been used to quickly assay metabolic pathway dynamics and elucidate rate-limiting enzymatic steps without the need for genome editing (Zalatan et al. 2015; Deaner and Alper 2017; Jensen et al. 2017). Also, single sets of transformation experiments (multiplex) can be easily implemented, and the one-time synthesis of gRNA sets allows rapid progression through iterative engineering cycles, namely by quickly assessing the combinatorial effects of expression perturbations in order to identify primary and secondary targets which could not be known *a priori* from single gene expression perturbations.

However, though several CRISPR proteins and gRNA versions have been tested in large-scale studies in yeast, the relative expression changes observed when using dCas9-mediated transcriptional regulation are still often observed to be at least an order of magnitude less than those observed for bacterial and mammalian reprogramming efforts, often in the 100–20 000-fold (Qi et al. 2013; Chavez et al. 2015), whereas highest transcript changes reported in yeast are ~100–250-fold (Gilbert et al. 2013; Chavez et al. 2015; Naranjo et al. 2015). In order to improve

the regulatory potential of CRISPR-dCas9 in yeast and to further potentiate the toolkit available for probing genome functions, there is still a need for further development of reprogramming technologies.

One new-in-class CRISPR technology of relevance for functional genomic studies was recently reported using orthologs of nuclease-proficient and -deficient RNase Cas13 from Type VI CRISPR-Cas systems, which can be guided by single-effector gRNAs to target more than 70% post-transcriptional knockdown of gene expression in mammalian and plant cells with high target specificity (Abudayyeh et al. 2017; Cox et al. 2017). Also, the Zhang laboratory showed that dCas13 could be fused to enzymes of the adenosine deaminase acting on RNA (ADAR) family and thereby enables RNA editing (Cox et al. 2017). As such, RNA-targeted dCas13 is believed to advance functional genomics at the post-transcriptional level supporting functional studies, e.g. mRNA splice variants, base editing at the RNA level and elucidating mRNA processing by way of dCas13 variants fused to regulatory domains, akin the design principles of dCas9 variants.

Also, though distinct from CRISPR, it should be mentioned that Barbieri et al. recently reported that silencing of yeast DNA repair machinery and slowing of replication enhances multiplex genome editing by 90-nt single-stranded oligodeoxynucleotides (ssODNs) in yeast, thereby enabling simultaneous integration of more than 10 ssODNs with up to 60 mutations per transformation (Barbieri et al. 2017). Most importantly, this strategy is both independent of DNA DSB and homologous recombination, and it should be possible in the near future to combine the multiloci and single-base pair resolution of this approach with CRISPR-dCas9-mediated transcriptional reprogramming for fast-track identification of genome and expression imprints related to desired traits.

Finally, native transcriptional regulation relies on integrate multigene spatio-temporal expression perturbations. To further enable synthetic and on-demand transcriptional control of polygenic traits, especially those dependent on essential genes, research within controllable CRISPR systems should take advantage of, and further develop, reprogramming strategies compatible with optogenetics, thereby circumventing the limited reversibility of the chemical-induced (e.g. aTc) systems (Xiaofeng et al. 2017). Likewise, allosteric regulation of CRISPR protein activity should be considered for conditional switching of cellular decision-making, e.g. growth and metabolic states (Oakes et al. 2016). Ultimately, such techniques are envisioned to dramatically support our understanding and orthogonal control of transcriptional and post-transcriptional regulations for desired cellular and metabolic outputs.

ACKNOWLEDGEMENTS

The authors would like to thank Emil Damgaard Jensen for fruitful discussions and comments to the manuscript during preparation.

FUNDING

This work was supported by the Novo Nordisk Foundation.

Conflict of interest. None declared.

REFERENCES

Abudayyeh OO, Gootenberg JS, Essletzbichler P et al. RNA targeting with CRISPR-Cas13. *Nature* 2017;550:280–4.

- Alper H, Moxley J, Nevoigt E et al. Engineering yeast transcription machinery for improved ethanol tolerance and production. *Science* 2006;314:1565–8.
- Barbieri EM, Muir P, Akhuetie-Oni BO et al. Precise editing at DNA replication forks enables multiplex genome engineering in eukaryotes. *Cell* 2017;171:1453–1467.e13.
- Blanchin-Roland S, Cordero Otero RR, Gaillardin C. Two upstream activation sequences control the expression of the XPR2 gene in the yeast *Yarrowia lipolytica*. *Mol Cell Biol* 1994;14:327–38.
- Blazek J, Liu L, Redden H et al. Tuning gene expression in *Yarrowia lipolytica* by a hybrid promoter approach. *Appl Environ Microbiol* 2011;77:7905–14.
- Chavez A, Scheiman J, Vora S et al. Highly efficient Cas9-mediated transcriptional programming. *Nat Methods* 2015;12:326–8.
- Chavez A, Tuttle M, Pruitt BW et al. Comparison of Cas9 activators in multiple species. *Nat Methods* 2016;13:563–7.
- Churchman LS, Weissman JS. Nascent transcript sequencing visualizes transcription at nucleotide resolution. *Nature* 2011;469:368–73.
- Cong L, Ran FA, Cox D et al. Multiplex genome engineering using CRISPR/Cas systems. *Science* 2013;339:819–23.
- Cox DBT, Gootenberg JS, Abudayyeh OO et al. RNA editing with CRISPR-Cas13. *Science* 2017;358 1019–27.
- Crook NC, Schmitz AC, Alper HS. Optimization of a yeast RNA interference system for controlling gene expression and enabling rapid metabolic engineering. *ACS Synth Biol* 2013;3:307–13.
- Dai X, Chen X, Fang Q et al. Inducible CRISPR genome-editing tool: classifications and future trends. *Crit Rev Biotechnol* 2017;38:573–86.
- Deaner M, Alper HS. Systematic testing of enzyme perturbation sensitivities via graded dCas9 modulation in *Saccharomyces cerevisiae*. *Metab Eng* 2017;40:14–22.
- Deaner M, Mejia J, Alper HS. Enabling graded and large-scale multiplex of desired genes using a dual-mode dCas9 activator in *Saccharomyces cerevisiae*. *ACS Synth Biol* 2017;6:1931–43.
- DiCarlo JE, Norville JE, Mali P et al. Genome engineering in *Saccharomyces cerevisiae* using CRISPR-Cas systems. *Nucleic Acids Res* 2013;41:4336–43.
- Drinnenberg IA, Weinberg DE, Xie KT et al. RNAi in budding yeast. *Science* 2009;326:544–50.
- Edmondson DG, Smith MM, Roth SY. Repression domain of the yeast global repressor Tup1 interacts directly with the histones H3 and H4. *Genes Dev* 1996;10:1247–59.
- Ellis T, Wang X, Collins JJ. Diversity-based, model-guided construction of synthetic gene networks with predicted functions. *Nat Biotechnol* 2009;27:465–71.
- Farzadfard F, Perli SD, Lu TK. Tunable and multifunctional eukaryotic transcription factors based on CRISPR/Cas. *ACS Synth Biol* 2013;2:604–13.
- Ferreira R, Skrekas C, Nielsen J et al. Multiplexed CRISPR/Cas9 Genome Editing and Gene Regulation Using Csy4 in *Saccharomyces cerevisiae*. *ACS Synth Biol* 2018;7:10–15.
- Flick JS, Johnston M. Two systems of glucose repression of the GAL1 promoter in *Saccharomyces cerevisiae*. *Mol Cell Biol* 1990;10:4757–69.
- Folcher M, Xie M, Spinnler A et al. Synthetic mammalian trigger-controlled bipartite transcription factors. *Nucleic Acids Res* 2013;41:e134.
- Fu BXH, Hansen LL, Artiles KL et al. Landscape of target:guide homology effects on Cas9-mediated cleavage. *Nucleic Acids Res* 2014a;42:13778–87.

- Fu Y, Rocha PP, Luo VM et al. CRISPR-dCas9 and sgRNA scaffolds enable dual-colour live imaging of satellite sequences and repeat-enriched individual loci. *Nat Commun* 2016;7:11707.
- Fu Y, Sander JD, Reyon D et al. Improving CRISPR-Cas nuclease specificity using truncated guide RNAs. *Nat Biotechnol* 2014b;32:279–84.
- Gander MW, Vrana JD, Voje WE et al. Digital logic circuits in yeast with CRISPR-dCas9 NOR gates. *Nat Comms* 2017;8:15459.
- Gao Y, Xiong X, Wong S et al. Complex transcriptional modulation with orthogonal and inducible dCas9 regulators. *Nat Methods* 2016;13:1043–9.
- Gao Y, Zhao Y. Self-processing of ribozyme-flanked RNAs into guide RNAs in vitro and in vivo for CRISPR-mediated genome editing. *J Integr Plant Biol* 2014;56:343–9.
- Gilbert LA, Horlbeck MA, Adamson B et al. Genome-scale CRISPR-mediated control of gene repression and activation. *Cell* 2014;159:647–61.
- Gilbert LA, Larson MH, Morsut L et al. CRISPR-mediated modular RNA-guided regulation of transcription in eukaryotes. *Cell* 2013;154:442–51.
- Griesenbeck J, Boeger H, Strattan JS et al. Affinity purification of specific chromatin segments from chromosomal loci in yeast. *Mol Cell Biol* 2003;23:9275–82.
- Hahn S. Structure and mechanism of the RNA polymerase II transcription machinery. *Nat Struct Mol Biol* 2004;11:394–403.
- Hinz JM, Laughery MF, Wyrick JJ. Nucleosomes inhibit Cas9 endonuclease activity in vitro. *Biochemistry* 2015;54:7063–6.
- Horlbeck MA, Gilbert LA, Villalta JE et al. Compact and highly active next-generation libraries for CRISPR-mediated gene repression and activation. *Elife* 2016;5. DOI: 10.7554/eLife.19760.
- Howe FS, Russell A, Lamstaes AR et al. CRISPRi is not strand-specific at all loci and redefines the transcriptional landscape. *Elife* 2017;6:e29878.
- Hsu PD, Scott DA, Weinstein JA et al. DNA targeting specificity of RNA-guided Cas9 nucleases. *Nat Biotechnol* 2013;31:827–32.
- Isaac RS, Jiang F, Doudna JA et al. Nucleosome breathing and remodeling constrain CRISPR-Cas9 function. *Elife* 2016;5:e13450.
- Jensen ED, Ferreira R, Jakóčiūnas T et al. Transcriptional reprogramming in yeast using dCas9 and combinatorial gRNA strategies. *Microb Cell Fact* 2017;16:46.
- Jensen MK, Kjaersgaard T, Nielsen MM et al. The arabidopsis thaliana NAC transcription factor family: structure-function relationships and determinants of ANAC019 stress signalling. *Biochem J* 2010;426:183–96.
- Jiang C, Pugh BF. A compiled and systematic reference map of nucleosome positions across the *Saccharomyces cerevisiae* genome. *Genome Biol* 2009;10:R109.
- Jinek M, Chylinski K, Fonfara I et al. A programmable dual-RNA-guided DNA endonuclease in adaptive bacterial immunity. *Science* 2012;337:816–21.
- Kadosh D, Struhl K. Repression by Ume6 involves recruitment of a complex containing Sin3 corepressor and Rpd3 histone deacetylase to target promoters. *Cell* 1997;89:365–71.
- Khalil AS, Lu TK, Bashor CJ et al. A synthetic biology framework for programming eukaryotic transcription functions. *Cell* 2012;150:647–58.
- Kiani S, Chavez A, Tuttle M et al. Cas9 gRNA engineering for genome editing, activation and repression. *Nat Methods* 2015;12:1051–4.
- Larson MH, Gilbert LA, Wang X et al. CRISPR interference (CRISPRi) for sequence-specific control of gene expression. *Nat Protoc* 2013;8:2180–96.
- Lawhorn IEB, Ferreira JP, Wang CL. Evaluation of sgRNA target sites for CRISPR-mediated repression of TP53. *PLoS One* 2014;9:e113232.
- Lee W, Tillo D, Bray N et al. A high-resolution atlas of nucleosome occupancy in yeast. *Nat Genet* 2007;39:1235–44.
- Lenstra TL, Coulon A, Chow CC et al. Single-Molecule imaging reveals a switch between spurious and functional ncRNA transcription. *Mol Cell* 2015;60:597–610.
- Lian J, Hamedirad M, Hu S et al. Combinatorial metabolic engineering using an orthogonal tai-functional CRISPR system. *Nat Comm* 2017;8:1688.
- Mao C, Brown CR, Griesenbeck J et al. Occlusion of regulatory sequences by promoter nucleosomes in vivo. *PLoS One* 2011;6:e17521.
- McIsaac RS, Oakes BL, Wang X et al. Synthetic gene expression perturbation systems with rapid, tunable, single-gene specificity in yeast. *Nucleic Acids Res* 2013;41:e57–.
- Mitsunobu H, Teramoto J, Nishida K et al. Beyond native Cas9: manipulating genomic information and function. *Trends Biotechnol* 2017;35:983–96.
- Nambu-Nishida Y, Nishida K, Hasunuma T et al. Development of a comprehensive set of tools for genome engineering in a cold- and thermo-tolerant *Kluyveromyces marxianus* yeast strain. *Sci Rep* 2017;7:8993.
- Naranjo S, Smith JD, Artieri CG et al. Dissecting the Genetic Basis of a Complex cis-Regulatory Adaptation. *PLoS Genet* 2015;11:e1005751.
- Nishida K, Arazoe T, Yachie N et al. Targeted nucleotide editing using hybrid prokaryotic and vertebrate adaptive immune systems. *Science* 2016;353:aaf8729.
- Oakes BL, Nadler DC, Flamholz A et al. Profiling of engineering hotspots identifies an allosteric CRISPR-Cas9 switch. *Nat Biotechnol* 2016;34:646–51.
- Ostling J, Carlberg M, Ronne H. Functional domains on the Mig1 repressor. *Mol Cell Biol* 1996;16:753–61.
- Pierre-Jerome E, Jang SS, Havens KA et al. Recapitulation of the forward nuclear auxin response pathway in yeast. *P Natl Acad Sci USA* 2014;111:9407–12.
- Qi LS, Larson MH, Gilbert LA et al. Repurposing CRISPR as an RNA-guided platform for sequence-specific control of gene expression. *Cell* 2013;152:1173–83.
- Radzisheuskaya A, Shlyueva D, Müller I et al. Optimizing sgRNA position markedly improves the efficiency of CRISPR/dCas9-mediated transcriptional repression. *Nucleic Acids Res* 2016;44:e141.
- Rando OJ, Chang HY. Genome-wide views of chromatin structure. *Annu Rev Biochem* 2009;78:245–71.
- Rando OJ, Winston F. Chromatin and transcription in yeast. *Genetics* 2012;190:351–87.
- Ryan OW, Skerker JM, Maurer MJ et al. Selection of chromosomal DNA libraries using a multiplex CRISPR system. *Elife* 2014;3:e03703.
- Schep AN, Buenrostro JD, Denny SK et al. Structured nucleosome fingerprints enable high-resolution mapping of chromatin architecture within regulatory regions. *Genome Res* 2015;25:1757–70.
- Schreiber-Agus N, Chin L, Chen K et al. An amino-terminal domain of Mxi1 mediates anti-Myc oncogenic activity and interacts with a homolog of the yeast transcriptional repressor SIN3. *Cell* 1995;80:777–86.
- Schwartz C, Frogue K, Ramesh A et al. CRISPRi repression of non-homologous end-joining for enhanced genome engineering via homologous recombination in *Yarrowia lipolytica*. *Biotechnol Bioeng* 2017;114:2896–906.

- Schwartz CM, Hussain MS, Blenner M et al. Synthetic RNA polymerase III promoters facilitate high-efficiency CRISPR–Cas9-mediated genome editing in *Yarrowia lipolytica*. *ACS Synth Biol* 2016;**5**:356–9.
- Si T, Luo Y, Bao Z et al. RNAi-assisted genome evolution in *Saccharomyces cerevisiae* for complex phenotype engineering. *ACS Synth Biol* 2015;**4**:283–91.
- Skjoedt ML, Snoek T, Kildegaard KR et al. Engineering prokaryotic transcriptional activators as metabolite biosensors in yeast. *Nat Chem Biol* 2016;**12**:951–8.
- Smith JD, Suresh S, Schlecht U et al. Quantitative CRISPR interference screens in yeast identify chemical-genetic interactions and new rules for guide RNA design. *Genome Biol* 2016;**17**:45.
- Smith JD, Schkecht U, Xu W et al. A method for high-throughput production of sequence-verified DNA libraries and strain collections. *Mol Syst Biol* 2017;**13**:913.
- Traven A, Staresinčić L, Arnerić M et al. The yeast protein Xtc1 functions as a direct transcriptional repressor. *Nucleic Acids Res* 2002;**30**:2358–64.
- Vanegas KG, Lehka BJ, Mortensen UH. SWITCH: a dynamic CRISPR tool for genome engineering and metabolic pathway control for cell factory construction in *Saccharomyces cerevisiae*. *Microb Cell Fact* 2017;**16**:25.
- Witzgall R, O'Leary E, Leaf A et al. The Kruppel-associated box-A (KRAB-A) domain of zinc finger proteins mediates transcriptional repression. *P Natl Acad Sci USA* 1994;**91**:4514–8.
- Wu J, Suka N, Carlson M et al. TUP1 utilizes histone H3/H2B-specific HDA1 deacetylase to repress gene activity in yeast. *Mol Cell* 2001;**7**:117–26.
- Wu X, Scott DA, Kriz AJ et al. Genome-wide binding of the CRISPR endonuclease Cas9 in mammalian cells. *Nat Biotechnol* 2014;**32**:670–6.
- Yoshioka S, Fujii W, Ogawa T et al. Development of a monopromoter-driven CRISPR/Cas9 system in mammalian cells. *Sci Rep* 2015;**5**:18341.
- Yuan G-C, Liu Y-J, Dion MF et al. Genome-scale identification of nucleosome positions in *S. cerevisiae*. *Science* 2005;**309**:626–30.
- Zalatan JG, Lee ME, Almeida R et al. Engineering complex synthetic transcriptional programs with CRISPR RNA scaffolds. *Cell* 2015;**160**:339–50.
- Zaugg JB, Luscombe NM. A genomic model of condition-specific nucleosome behavior explains transcriptional activity in yeast. *Genome Res* 2012;**22**:84–94.
- Zhang Z, Reese JC. Molecular genetic analysis of the yeast repressor Rfx1/Crt1 reveals a novel two-step regulatory mechanism. *Mol Cell Biol* 2005;**25**:7399–411.
- Zhang T, Gao Y, Wang R et al. Production of guide RNAs in vitro and in vivo for CRISPR using ribozymes and RNA polymerase II promoters. *Bio Protoc* 2017;**7**:e2148.